A Generalized Canopy Model for the Wind Resource Assessments in Forest and Urban Area

Kota Enoki enoki@bridge.t.u-tokyo.ac.jp
Takeshi Ishihara ishihara@bridge.t.u-tokyo.ac.jp
Atsushi Yamaguchi atsushi@bridge.t.u-tokyo.ac.jp

Dept. of Civil Eng., The University of Tokyo 7-3-1 Hongo, Bunkyo-ku, Tokyo 113-8656 JAPAN

Introduction

In Japan, the installed capacity of wind energy has reached 1.67 GW at March 2007. As the development of wind energy is increasing, the need for the prediction of wind field near urban area or dense forest is also increasing. Several models have been used for this purpose. Canopy models are one of such models, which treat the effect of obstacle as the external source term. However conventional canopy models have the disadvantage of inapplicability to the high packing density canopy. In this study, a new generalized canopy model is proposed and verified, which can deal with the grids with high packing density and can express the effect of the vegetation, buildings and porous media.

Generalized canopy model

Governing Equations

Mass conservation

$$\frac{\partial \rho \bar{u}_i}{\partial x_i}=0$$

Momentum conservation

$$\frac{\partial \rho \bar{u}_i}{\partial t}+\frac{\partial \rho \bar{u}_j \bar{u}_i}{\partial x_j}=-\frac{\partial \bar{p}}{\partial x_i}+\frac{\partial}{\partial x_j}\left(\mu \frac{\partial \bar{u}_i}{\partial x_j}-\rho \overline{u'_i u'_j}\right)+f_{u,i}$$

Turbulent kinetic energy k

$$\frac{\partial \rho k}{\partial t}+\frac{\partial \rho \bar{u}_j k}{\partial x_j}=\frac{\partial}{\partial x_j}\left|\left(\mu+\frac{\mu_t}{\sigma_k}\right)\frac{\partial k}{\partial x_j}\right|-\rho \overline{u_i' u_j'}\frac{\partial \bar{u}_i}{\partial x_j}-\rho\varepsilon+f_k$$

Energy dissipation rate ε

$$\frac{\partial \rho \varepsilon}{\partial t}+\frac{\partial \rho \bar{u}_j \varepsilon}{\partial x_j}=\frac{\partial}{\partial x_j}\left|\left(\mu+\frac{\mu_t}{\sigma_\varepsilon}\right)\frac{\partial \varepsilon}{\partial x_j}\right|-C_{\varepsilon 1}\frac{\varepsilon}{k}\rho \overline{u'_i u'_j}\frac{\partial \bar{u}_i}{\partial x_j}-C_{\varepsilon 2}\frac{\rho \varepsilon^2}{k}+f_\varepsilon$$

Reynolds stress is evaluated by the Launder and Kato[1] model. The terms $f_{u,i}$, f_k and f_ε are the external force/effects by objects modeled in this study. Model parameters are the same as the standard k - ε model.

Variables in this study

Variable	Description	Variable	Description
V_{grid}	Total volume of grid	γ_f	Porosity
V_f	Total volume of fluid	γ_o	Packing density
V_o	Total volume of obstacles	C_f	Drag coefficient
A_o	The reference area of obstacles	l_o	Length scale of obstacles
ρ	Air density	C	Empirical constant
$\overline{u_i}$	Mean velocity in i direction	$\overline{D}$	Mean diameter of porous media
u_i'	Fluctuating component of u_i	C_S	Shape parameter
$\overline{p}$	Pressure	V_{porous}	Total volume of porous media
k	Turbulent kinetic energy	S_{porous}	Total surface area of porous media
ε	Dissipation rate of k	$C_{D,t}$	Drag coefficient of vegetation
C_D	Drag coefficient	a_t	Leaf area density
$\tilde{\phi}$	Variable ϕ averaged in V_f	a_b	Specific surface of the buildings

Generalization of fluid force

A fluid force model is proposed, based on the drag force F_{Drag}.

Fluid force

$$f_{u,i}=\frac{F_{\text{Drag}}}{V_{\text{grid}}}=\frac{-\frac{1}{2}\rho C_D A_o \sqrt{\widetilde{u_j}^2}\,\widetilde{u_i}}{V_{\text{grid}}}=\frac{-\frac{1}{2}\rho C_D \gamma_o A_o l_o \sqrt{\overline{u_j}^2}\,\overline{u_i}}{(1-\gamma_o)^2\gamma_o V_{\text{grid}} l_o}=-\frac{1}{2}\rho C_f \frac{1}{l_o}\gamma_o \sqrt{\overline{u_j}^2}\,\overline{u_i}$$

Drag coefficient

$$C_f=\frac{C_D}{(1-\gamma_o)^2}$$

Length scale of obstacles

$$l_o=\frac{V_o}{A_o}=\frac{\gamma_o V_{\text{grid}}}{A_o}$$

Interpretation of the conventional canopy models

Conventional models are interpreted with the proposed model and the physical meanings of the length scale of obstacles are given as below

Interpretation of the conventional models

Obstacle Type	Original Expression	Equivalent parameters	Interpretation
Porous media[3]	$f_{u,i}=-\frac{C\rho}{\overline{D}}\frac{1-\gamma_f}{\gamma_f^3}\sqrt{\overline{u_j}^2}\,\overline{u_i}$, $\overline{D}=\frac{C_S V_{\text{porous}}}{S_{\text{porous}}}$	$C_f=\frac{4C}{3(1-\gamma_o)^3}$, $l_o=\frac{\overline{D}}{6}$	If the porous medium is sphere, the length scale is the one sixth of its diameter.
Vegetation	$f_{u,i}=-\frac{1}{2}\rho C_{D,t} a_t \sqrt{\overline{u_j}^2}\,\overline{u_i}$, $a_t=\frac{S_{\text{Leaf}}}{V_{\text{Grid}}}$	$C_f=C_{D,t}$, $l_o=\frac{\gamma_o}{a_t}$	The length scale is interpreted as the average thickness of leaves.
Buildings[2]	$f_{u,i}=-\frac{1}{2}\rho C_D a_b \sqrt{\widetilde{u_j}^2}\,\widetilde{u_i}$, $a_b=\frac{A_r}{(1-\gamma_o)V_{\text{grid}}}$	$C_f=\frac{C_D}{(1-\gamma_o)^2}$, $l_o=\frac{1-\gamma_o}{\gamma_o a_b}$	The length scale corresponds to the averaged depth of buildings

Turbulence

The source terms of the turbulent properties are evaluated with Green's model[4].

Effects on turbulence properties (Green[4])

$$f_k=\beta_p \rho \frac{C_f \gamma_o}{2 l_o}\frac{\varepsilon}{k}\sqrt{\overline{u_j}^2}^3\left(1-\frac{\beta_d}{\beta_p}\frac{k}{\sqrt{\overline{u_j}^2}^2}\right)$$

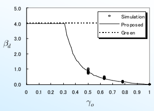
$$f_\varepsilon=C_{p\varepsilon 1}\beta_p \rho \frac{C_f \gamma_o}{2 l_o}\frac{\varepsilon}{k}\sqrt{\overline{u_j}^2}^3\left(1-\frac{C_{p\varepsilon 2}}{C_{p\varepsilon 1}}\frac{\beta_d}{\beta_p}\frac{k}{\sqrt{\overline{u_j}^2}^2}\right)$$

To deal with the grids with high packing density, the terms in f_k are assumed to be in balance with each other at high packing density. The model parameter β_d is modeled as:

Modification of coefficient

$$\beta_d=\min(4.0,\beta_d')$$

$$\beta_d'=C_{m1}\exp\left(\frac{1-\gamma_o}{\gamma_o}\right)+C_{m2}$$

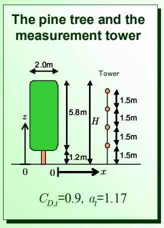


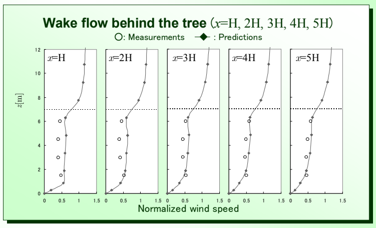
The proposed $f_{u,i}$, f_k and f_ε are applicable to any obstacles with any packing density. In this sense, it is called as "The Generalized Canopy Model".

Verification for single objects

Flow around a pine tree

The flow behind a pine tree is simulated by the proposed model.

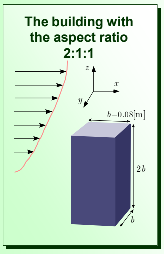


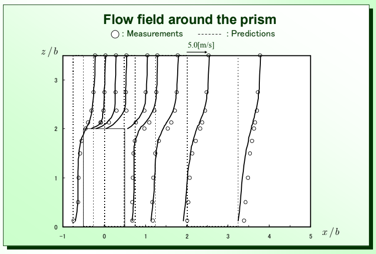


The results show good agreements with the measurements[5]

Flow around a building

For the verification of the model with high packing densities, flow around a prism is simulated and compared with the measurement[6].





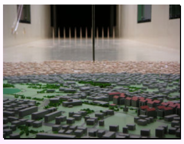
The proposed model can predict flow reasonably without any complicated computational grid or boundary conditions.

Verification for urban area

Wind tunnel test of urban area

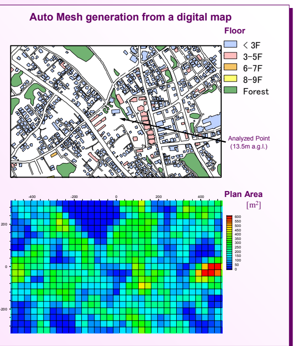
The proposed model is verified by a wind tunnel test with an scaled urban model.


Scale model


Wind tunnel

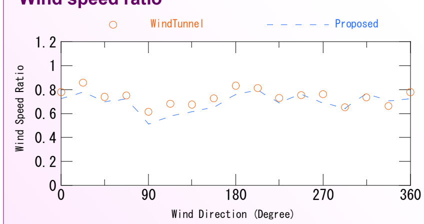
Computational domain

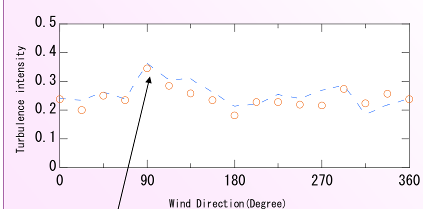
Arrangement, geometry and height of the buildings are obtained from a digital map called "Zmap-TOWN2" (Zenrin corporation).



Results

The wind tunnel test is simulated by the proposed model and compared with the measurements.





The simulated wind speed ratio and the turbulence intensity show the shading effect by high rise buildings.

Conclusions

In this study, a generalized canopy model for the prediction of the wind field is proposed and following conclusions are obtained.

1. Generalized canopy model is proposed and any conventional external force models can be interpreted through the proposed model.
2. Flow around different kind of obstacles are simulated and results show good agreements with the measurements.
3. A wind tunnel test of the city model is also performed and simulated. The proposed model shows good agreement with the measurement.

Reference

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